

NASA'S SPACE LAUNCH SYSTEM: AN EVOLVING CAPABILITY FOR EXPLORATION

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Abstract

A foundational capability for international human deep-space exploration, NASA's Space Launch System (SLS) vehicle represents a new spaceflight infrastructure asset, creating opportunities for mission profiles and space systems that cannot currently be executed. While the primary purpose of SLS, which is making rapid progress towards initial launch readiness in two years, will be to support NASA's Journey to Mars, discussions are already well underway regarding other potential utilization of the vehicle's unique capabilities. In its initial Block 1 configuration, capable of launching 70 metric tons (t) to low Earth orbit (LEO), SLS will propel the Orion crew vehicle to cislunar space, while also delivering small CubeSat-class spacecraft to deep-space destinations. With the addition of a more powerful upper stage, the Block 1B configuration of SLS will be able to deliver 105 t to LEO and enable more ambitious human missions into the proving ground of space. This configuration offers opportunities for launching co-manifested payloads with the Orion crew vehicle, and a class of secondary payloads, larger than today's CubeSats. Further upgrades to the vehicle, including advanced boosters, will evolve its performance to 130 t in its Block 2 configuration. Both Block 1B and Block 2 also offer the capability to carry 8.4- or 10-m payload fairings, larger than any contemporary launch vehicle. With unmatched mass-lift capability, payload volume, and C3, SLS not only enables spacecraft or mission designs currently impossible with contemporary EELVs, it also offers enhancing benefits, such as reduced risk, operational costs and/or complexity, shorter transit time to destination or launching large systems either monolithically or in fewer components. This paper will discuss both the performance and capabilities of Space Launch System as it evolves, and the current state of SLS utilization planning.

I. BACKGROUND

As NASA's Space Launch System Program continues production of flight hardware and testing in advance of the first launch of the vehicle in two years, increasing focus is being placed on the capabilities of the evolved configurations of the vehicle which will conduct human exploration missions into the Proving Ground of Deep Space and which will ultimately enable astronauts to take their first steps on Mars.

These capabilities, vital to human missions beyond low Earth orbit, will also provide game-changing benefits for other mission profiles beyond the capabilities of current launch vehicles.

The initial configuration of the vehicle, on track for launch readiness in 2018, is designed to offer substantial launch capability in an expeditious timeframe. The launch system is designed to then evolve into configurations offering greater launch capability via an affordable and sustainable development path.

Currently under construction, the initial Block 1 configuration of the vehicle will have the capability to deliver a minimum of 70 t into low Earth orbit and will be able to launch a crew aboard the Orion spacecraft

into cislunar space on its first flight, Exploration Mission-1. (Fig. 1) The vehicle will evolve to a full Block 2 capability of greater than 130 t to LEO and will be able to support a stepping-stone approach to human exploration leading to Mars.

NASA is developing SLS, which is managed at Marshall Space Flight Center in Huntsville, Ala., in parallel with two other exploration systems development efforts – the Orion Multi-Purpose Crew Vehicle (MPCV) Program, managed at Johnson Space Center in Houston, Texas, and the Ground Systems Development and Operations (GSDO) Program. The Orion MPCV is a four-person spacecraft designed to carry astronauts on exploration missions into deep space. GSDO is converting the facilities at NASA's Kennedy Space Center (KSC) in Florida into a next-generation spaceport capable of supporting launches by multiple types of vehicles.

These capabilities are part of a larger NASA strategy of working with commercial partners that will support crew and cargo launches to the International Space Station, while the Agency focuses its development efforts on an incremental approach to developing the

systems necessary for human exploration beyond Earth orbit and eventually to Mars. Both Orion and SLS are being designed with performance margin and flexibility



Figure 1. Artist's rendition of Space Launch System on its mobile launcher.

to support an evolvable human exploration approach.

II. VEHICLE OVERVIEW AND STATUS

The architecture of the SLS initial Block 1 configuration reflects NASA's desire to meet the mandates for heavy-lift capability in the U.S. congressional NASA Authorization Act of 2010 in a manner that is safe, affordable, and sustainable. After input was received from industry and numerous concepts were reviewed, a shuttle-derived design was found to enable the safest, most-capable transportation system in the shortest amount of time for the anticipated near-term and long-range budgets.

The SLS operational scheme takes advantage of resources established for the Space Shuttle Program, including workforce, tooling, manufacturing processes, supply chains, transportation logistics, launch infrastructure, and liquid oxygen and hydrogen (LOX/LH2) propellants and allows the initial configuration of the vehicle to be delivered with only one clean-sheet new development, the Core Stage. In October 2015, the SLS Program completed its Critical

Design Review (CDR), the first time a NASA human-class launch vehicle has reached that milestone since the Shuttle Program almost 40 years ago and the first for an exploration-class vehicle since the Saturn V.

The SLS Core Stage, which stores the liquid oxygen (LOX) and liquid hydrogen (LH2) propellant for four Core Stage engines, represents almost two-thirds of the vehicle's 98-meter height, standing 64m tall, and will have a diameter of 8.4m, sharing commonality with the space shuttle's external tank in order to enhance compatibility with equipment and facilities at KSC and elsewhere. At MAF, outside New Orleans, Louisiana, the world's largest space vehicle welding tool, the 52m-tall Vertical Assembly Center (VAC), is currently being used by The Boeing Company, Core Stage prime contractor, to weld barrel sections, rings and domes together to form the test and flight articles of the propellant tanks for the stage. (Fig. 2)

The Core Stage will be powered by four RS-25 engines, which previously served as the Space Shuttle Main Engine (SSME), taking advantage of 30 years of



Figure 2. Production of the structural test article of the liquid hydrogen tank for the SLS Core Stage.

U.S. experience with liquid oxygen and liquid hydrogen, as well as an existing U.S. national infrastructure that includes specialized manufacturing and launching facilities. These human-rated engines support the SLS pursuit of safety, with a record of 100 percent mission success for the engines over 135 flights. At the end of the Space Shuttle Program, 16 RS-25 flight engines and two development engines were transferred to the SLS Program and placed in inventory at NASA's Stennis Space Center, providing enough engines for the first four flights of SLS.

Modifications to Stennis Test Stand A-1 to support RS-25 testing were completed in 2014, and testing has been underway since the beginning of 2015 in preparation for flight certification of the SLS configuration of the engine, including a new engine controller unit. (Fig. 3) The testing includes propellant pressure and temperature inlet conditions that will both be higher with SLS than with the shuttle, as well as other SLS-specific performance requirements such as 109 percent thrust versus the shuttle's 104.5 percent thrust. Stennis Test Stand B-2 is being refitted for the SLS "green run" – the test firing of the first Core Stage with four RS-25 engines. The test, which will begin in late 2017, will be the largest liquid-engine test since stage tests of the Saturn V in the 1960s.

The majority of the thrust for the first two minutes of flight will come from a pair of Solid Rocket Boosters, also of Space Shuttle Program heritage. The SLS is upgrading the boosters from the four-segment version flown on the shuttle to a more-powerful five-segment version. Each booster measures 54 m long and 3.7 m in diameter and is capable of generating up to 3.6 million pounds of thrust, the most powerful flight boosters in the world. Although largely similar to the SRBs used on the space shuttle, this upgraded five-segment SRB includes improvements such as a larger nozzle throat and an environmentally-benign insulation and liner material (asbestos-free). In June 2016, the SLS configuration of the booster successfully underwent the second of two Qualification Motor tests, and booster hardware is currently being prepared for first flight. (Fig. 4)

In-space propulsion for the Block 1 vehicle will be provided by an Interim Cryogenic Propulsion Stage (ICPS). (Fig.5) In order to expedite earlier initial launch of this new U.S. super-heavy-lift launch capability, the decision was made early in the vehicle's development to leverage the proven Delta Cryogenic Second Stage (DCSS) for SLS in-space propulsion, delaying development of a larger upper stage until the vehicle's Core Stage, the largest new development for the Block 1 vehicle, was more mature. That decision has allowed the program to move toward initial launch readiness, with the capability to send the Orion crew vehicle farther into space than Apollo travelled. The



Figure 3: RS-25 testing at Stennis Space Center



Figure 4: Qualification Motor-2 test of the SLS solid rocket boosters.



Figure 5: Event at United Launch Alliance in Decatur, AL marking completion of the ICPS test article.

Block 1 Spacecraft/Payload Elements include not only the ULA-produced DCSS-derived ICPS but also two adapters, connecting the stage to the Core Stage and to the Orion spacecraft.

The Launch Vehicle Stage Adapter, which connects the Core Stage with the ICPS, is being produced by Teledyne Brown Engineering of Huntsville, Ala., and is being welded on-site at Marshall Space Flight Center. A structural test article has been completed, and

assembly of the EM-1 flight article is underway. The Orion Stage Adapter, which connects the Orion spacecraft with the ICPS, is being produced by Marshall Space Flight Center. An Orion Stage Adapter produced by the SLS Program flew successfully on the Exploration Flight Test-1 of Orion in December 2014; and the EM-1 flight unit has been welded at Marshall.

The ICPS is being produced by United Launch Alliance in Decatur, Ala., under contract to Boeing. The structural test article of the ICPS arrived at Marshall for testing in June 2016, and the flight unit is currently being assembled.

III. VEHICLE EVOLUTION

The evolved configurations of SLS, including both the 105 t Block 1B and the 130 t Block 2, offer opportunities for launching co-manifested payloads and a new class of secondary payloads with the Orion crew vehicle, and also offer the capability to carry primary payloads within 8.4- or 10-m payload fairings, larger than any contemporary launch vehicle, delivering unmatched mass-lift capability, payload volume, and C3 departure energy. (Fig. 6)

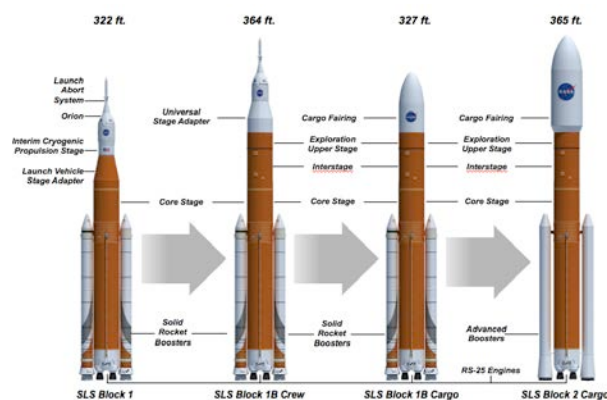


Figure 6: SLS Evolutionary Path

As early as the second launch of SLS, Exploration Mission-2, the vehicle will be augmented with a low-thrust dual-use Exploration Upper Stage (EUS), providing both ascent and in-space propulsion capabilities. This stage, which is working toward a preliminary design review in late 2016, will upgrade SLS to a performance of 105 t to LEO, and create a configuration that will serve as a workhorse for “Proving Ground” missions in cislunar space that will pave the way for further exploration. From there, additional upgrades, including enhancements to the RS-25 engines and upgraded boosters will ultimately evolve SLS to a configuration capable of delivering more than 130 metric tons to LEO, the capability identified as necessary for human missions to Mars.

Early research has also been conducted into options for larger 8.4- and 10-m fairings, with which SLS will

potentially offer payload volumes of 1,200 and 1,800 cubic meters, respectively. With a 10-m fairing, the vehicle will be able to offer payload volumes five times greater than currently available. In addition to those traditional classes of payload fairings, the Space Launch System offers additional unique payload capabilities, including launch of a co-manifested payload along with the Orion spacecraft or delivery of secondary payloads to lunar or planetary trajectories. A co-manifested payload, with a volume of up to 400 cubic meters, could be placed within the Universal Stage Adapter connecting the Exploration Upper Stage to the Orion stack, and could be used, among other purposes, to deliver multi-ton payloads to a destination alongside Orion, allowing, for example, deployment of Orion and a habitat with crew to cislunar space with a single launch.

Work is already underway on these future configurations of the vehicle. System requirement and design reviews for the Exploration Upper Stage were completed in late 2015, and the Program is working toward a preliminary design review on the stage in late 2016. Boeing is the contractor for the EUS, with Aerojet Rocketdyne providing the RL-10-C3 engines. NASA’s Glenn Research Center will manage the Universal Stage Adapter (USA), and is preparing for a request for proposal for the USA in October 2016. Early risk reduction and engineering demonstration work has also been conducted for concepts related to future booster upgrades.

IV. CAPABILITIES AND UTILIZATION

The capabilities of the Space Launch System provide not only the capability to conduct human exploration of deep space, but also game-changing benefits for a range of promising space science missions. Three major interrelated areas have been identified in which SLS offers unique benefits that make possible new missions or mission profiles – unrivaled mass-lift capability, payload volume capacity, and departure energy. Taking advantage of these benefits allows spacecraft designers and mission planners to change fundamental assumptions about spacecraft and mission design, as these areas offer the potential for numerous benefits:

- Less-complex payload design and miniaturization needed to fit in fairings, leading to increased design simplicity.
- Decreased launches for in-space assembly, resulting in reduced risk.
- Less folding/deployment complexity, leading to increased mission reliability and confidence.
- High-energy orbit and shorter trip times, leading to less expensive mission operations and reduced exposure to the space environment.

- Increased lift capacity and payload margin, resulting in less risk.

The high mass-lift capability of SLS is vital to human deep-space exploration, allowing the launch of the Orion crew vehicle and other exploration systems to a staging location in the lunar vicinity, or directly into deep space. Not only will SLS be able to launch large systems in a cargo configuration, it will be able to launch payloads, such as smaller habitat modules, co-manifested with Orion within the Universal Stage Adapter connecting the crew vehicle with the rocket's upper stage. This adapter offers greater payload volume than any contemporary EELV payload fairing, opening opportunities for single-launch of longer-duration deep-space stays.

SLS' characteristic energy (C3) offers reduced mission transit time, thereby reducing power requirements as well as the amount of time that scientific instruments are exposed to space. While commercial launchers will continue to serve as the workhorse for many of NASA's science missions, those spacecraft often have to make multiple gravity-assist maneuvers around inner planets before reaching the velocity needed for the transit to the outer planets. These maneuvers increase mission times by years and increase risk to onboard instruments because of the extended time in the space environment and the range of conditions to which they require exposure.

SLS utilization is currently being considered for NASA's proposed Europa Multiple Flyby Mission, which would provide an unprecedented look at the icy Jovian moon, believed to hold a subsurface ocean with more than twice the quantity of water on Earth, and investigate its potential habitability.

While launch on an Atlas V 551 EELV-baseline vehicle could require a Venus-Earth-Earth gravitational assist trajectory requiring 7 to 8 years, launch on SLS would enable a direct transit to the Jovian system in less than three years, providing far earlier science return and reduced operational costs, among other benefits (Fig. 7). With consideration currently ongoing of a follow-up Europa lander mission, the earlier science return could allow use of data from the flyby mission to inform the lander mission, without a substantial delay to the latter.

Europa mission analysis also serves as a test case for how SLS could benefit outer-planet exploration. One of the major benefits to the science community from the Mars Program has been the ability to learn from one mission and use that knowledge when formulating a near-term future investigation. The paradigm for outer planet exploration has necessitated very long cruise times, which, among other things, make it impossible to have a rapid turnaround in penetrating the mysteries that the "ocean world" icy moons of the outer planets possess. The availability of the SLS breaks this model, and allows for significant transit-time reduction.

In the area of payload volume capacity, a large-aperture space telescope offers a good case study. Concept evaluation has demonstrated potential benefits of a large 8.4- or 10-m SLS payload fairing for the

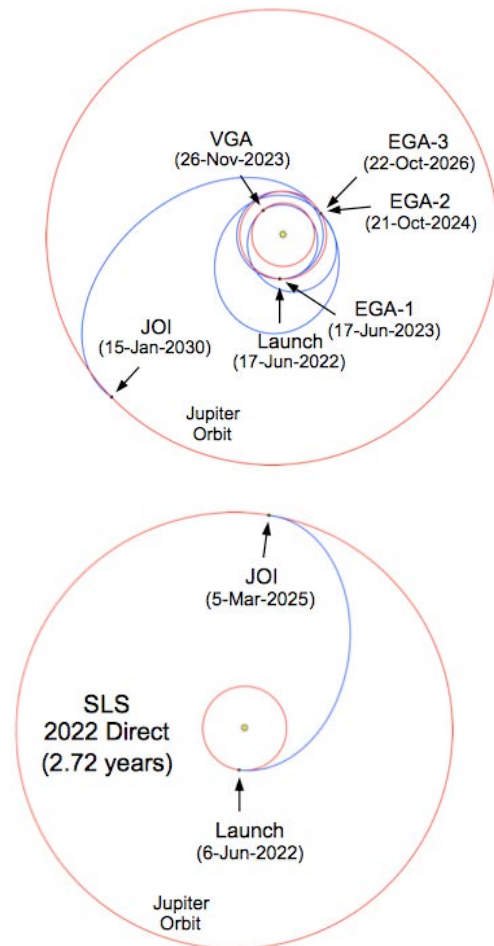


Figure 7. Gravitational-assist trajectory to Europa enabled by current EELVs (top) versus direct trajectory enabled by SLS (bottom).

science community. (Fig. 8) Such a fairing would enable the launch of a large aperture (potentially 16-m class) telescope that would be able to make ultra-high-contrast spectroscopic observations of exoplanets. Such a capability would address a need identified in the 2013 NASA astrophysics roadmap, "Enduring Quests, Daring Visions." Concept evaluations of such a project have also identified opportunities for further collaborations between science and human exploration systems in the form of assembly and servicing of an observatory in deep space.

While the most obvious mission profiles to benefit from SLS are those with requirements beyond the performance of current launch vehicles, SLS will also

offer unique opportunities for smaller experiments in the form of secondary payload berths. Thirteen secondary payload locations will be available in the Orion-to-Stage Adapter in the initial SLS configuration,



Figure 8. Fairing options for evolved configurations of Space Launch System.

allowing payload deployment following Orion separation. The deployment berths are sized for “6U” CubeSats, and on EM-1 the spacecraft will be deployed into cislunar space following Orion separate from the SLS Interim Cryogenic Propulsion Stage. Payloads in 6U class will be limited to 14 kg maximum mass. Concepts are still being reviewed for secondary payload accommodations on the evolved configurations of SLS. There is potential for these configurations to carry a larger class of secondary payload, which could also be deployed either into cislunar space with Orion or to another deep-space destination, accompanying a primary science payload.

CubeSat payloads on EM-1 will include both NASA research experiments and spacecraft developed by industry, international and potentially academia partners. The Human Exploration and Operations Mission Directorate (HEOMD) Advanced Exploration Systems (AES) Division was allocated five payload opportunities on the EM-1 mission.

Near Earth Asteroid (NEA) Scout is a 6U cubesat designed to rendezvous with and characterize a candidate NEA. A solar sail, another innovation to be demonstrated in the cubesat class, will provide propulsion.

Lunar Flashlight is the second AES payload planned for manifest on EM-1. It will use a green propellant

system and will search for potential ice deposits in the Moon’s permanently shadowed craters.

The third payload being developed by AES is BioSentinel. The payload is a yeast radiation biosensor, planned to measure the effects of space radiation on Deoxyribonucleic acid (DNA).

Lunar Icecube, a collaboration with Moorehead State University, will prospect for water in ice, liquid, and vapor forms as well as other lunar volatiles from a low-perigee, highly inclined lunar orbit using a compact Infrared spectrometer. Skyfire, a partnership with Lockheed Martin, is a technology demonstration mission that will perform a lunar flyby, collecting spectroscopy, and thermography data to address questions related to surface characterization, remote sensing, and site selection.

NASA’s Space Technology Mission Directorate (STMD) was allocated three payload opportunities on the EM-1 mission. NASA’s STMD is innovating, developing, testing, and flying hardware for use in NASA’s future missions through the Centennial Challenges Program. The Centennial Challenges Program is NASA’s flagship program for technology prize competitions, which directly engages the public, academia, and industry in open prize competitions to stimulate innovation in technologies that have benefit to NASA and the nation. STMD has released the CubeSat Lunar Challenge to foster innovations in small spacecraft propulsion and communications. Potential candidates for the three STMD opportunities on the EM-1 mission will compete in a series of four Ground Tournaments before final selection is made. Final selection will be made in March of 2017.

The NASA Science Mission Directorate (SMD) was allocated two payload opportunities on the EM-1 mission.

The Cubesat Mission to Study Solar Particles (CuSP) payload will study the sources and acceleration mechanisms of solar and interplanetary particles in near-Earth orbit, support space weather research by determining proton radiation levels during Solar Energetic Particle (SEP) events and identifying suprathermal properties that could help predict geomagnetic storms.

The LunaH-Map payload will help scientists to understand the quantity of H-bearing materials in lunar cold traps (~10 km), determine the concentration of H-bearing materials with 1m depth, and constrain the vertical distribution of H-bearing materials.

The final three payload opportunities for the EM-1 mission were allocated for NASA’s international space agency counterparts. The flight opportunities are intended to benefit the international space agency and NASA as well as further the collective space exploration goals. A joint process with NASA and the international partners was employed to review, evaluate,

and recommend the payloads to fly on EM-1. From that joint process three payloads were chosen: Omotenashi, (formerly SLS Launched Innovative Mission [SLSLIM]), ArgoMoon, and EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS).

ArgoMoon is sponsored by ESA/ASI and will fly-along with the ICPS on its disposal trajectory to perform proximity operations with the ICPS post-disposal, take external imagery of engineering and historical significance, and perform an optical communications demonstration.

The EQUULEUS spacecraft sponsored by JAXA will fly to a libration orbit around the Earth-Moon L2 point and demonstrate trajectory control techniques within the Sun-Earth-Moon region for the first time by a nano spacecraft. The mission will also contribute to the future human exploration scenario by understanding the radiation environment in geospace and deep space, characterizing the flux of impacting meteors on the far side of the moon, and demonstrating the future deep space exploration scenario using the “deep space port” at Lagrange points.

The Omotenashi mission sponsored by JAXA will land the smallest lunar lander to date on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration system. Small landers will enable multi-point exploration, which is complimentary with large-scale human exploration. Once on the lunar surface, the Omotenashi spacecraft will observe the radiation and soil environments of the lunar surface by active radiation measurements and soil shear measurements.

While the Orion Stage Adapter on which the EM-1 Cubesats will be berthed will not be flown on the evolved configuration of the vehicle, the Program plans to fly larger secondary payloads on future configurations, and is working to mature plans for accommodations.

IV. CONCLUSION

Substantial progress has been made on the development and manufacture of the initial 70 t Block 1 configuration of SLS, and its first launch will be a significant step in demonstrating the super-heavy-lift capability needed for human exploration of deep space. With the evolution of SLS beginning with its second launch, this vehicle will return humans to deep space for the first time in decades, beginning a series of exploration missions that will lead to Mars and other destinations and reveal an unprecedented wealth of knowledge about our solar system and universe.